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13. ABSTRACT *(Maximum 200 words)*

This report summarizes our research during the past year on the interaction of 80 ns pulses of infrared radiation produced by a CO_2-TEA laser with the cornea. Epithelial damage thresholds were determined for sequences of 1, 2, 8, 32, 128, and 1024 pulses at 10 Hz and for sequences of 1, 2, 8, 32, 128, and 1024 pulses at 16 Hz. Threshold damage is correlated by a power law of the form $ED_{th} = CN^{-\alpha}$ in which ED_{th} is the threshold energy density and N is the number of pulses in the sequence. Temperature calculations reveal that the maximum temperature increase on the beam axis 10 μm beneath the anterior tear surface resulting from the different threshold exposures is essentially constant. This result is consistent with a critical peak temperature damage model and suggests that, at least for the multiple-pulse exposures, the damage mechanism may be predominately thermal. Damage threshold measurements on corneas maintained at 21 C indicated that the damage mechanism is indeed predominately thermal.

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FOREWORD

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Russell L. McCalley
Principal Investigator's Signature

December 3, 1997
Date

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Introduction

The military employs a broad range of laser radiation in training devices, rangefinders, target designators, communications devices and other instruments. This equipment emits either single pulses or sequences of pulses in beams of various diameters. The research performed under this contract directly supports the U. S. Army Medical Research and Materiel Command (USAMRMC) mission to assess the health effects and hazards of nonionizing electromagnetic radiation from such laser systems. The data obtained will support evaluation of current permissible exposure limits and will aid health policy makers, both within and outside the DoD, in developing injury prevention criteria. The general approach is to make direct determinations of damage threshold levels for non-ionizing radiation for specific exposure conditions (e.g., wavelengths, pulse durations, etc.) and to develop models of the damage mechanism that enable the extension of the results to other exposure conditions.

Under past support from the Army Medical Research and Development Command we determined corneal damage thresholds for CO_2 lasers that emit single and sequences of pulses having durations of 1 ms and longer and developed thermal damage models for predicting this type of damage[1-5]. We also determined corneal damage thresholds for single 80 ns pulses of CO_2 laser radiation and for three multiple-pulse (2 pulses at 1 Hz.; and 2 and 8 pulses at 10 Hz.).[6, 7] In the case of these very short pulses, damage mechanisms other than thermal (e.g., acoustical pressure pulses) could also play a role. Light and electron microscopy revealed unusual disruptions of the anterior epithelial surface for the threshold single-pulse exposure. The characteristics of these disruptions differed from those observed with simple thermal damage at longer pulse durations and appeared to be consistent with a mechanical [e.g., acoustic] damage mechanism. However, the calculated temperature increase produced by the threshold exposure was only slightly lower than that calculated for threshold exposures having durations of 1 ms and longer.[6, 7] Thus we could not exclude a thermal damage mechanism, with the sharp temperature gradients leading to marked differences in the character of the damage as compared to damage from longer duration exposures.

This study aims to expand the database of thresholds for sequences of 80 ns of CO_2 laser pulses to include larger numbers of pulses and other pulse repetition frequencies. In addition it will attempt to clarify the damage mechanism(s) for these types of pulses and ultimately will begin to address damage from mid-infrared wavelengths where the radiation is more penetrating.

Methods

Short-pulse exposures are made with a Boston Laser (Model 220S) CO_2-TEA laser operated in the TEM_{00} mode. This laser delivers 80 ns pulses at pulse repetition frequencies up to 16 Hz. Mode quality is verified and the beam diameter is measured at the beginning, middle and end of each experimental session using a Spiricon linear pyroelectric array. The detector has 64 elements on 200 μm centers. It is mounted on a vertical micropositioner and is read out with a LeCroy 9354M digital oscilloscope. Pulse energy is measured with a Scientech detector immediately before and immediately after each exposure.

New Zealand white rabbits of either sex weighing 4 - 5 pounds are used for the experiments. The rabbits are treated in accordance with the *Guide for the Care and Use of Laboratory Animals* (DHEW Publication No. (NIH) 85-23, Revised Edition, 1985 and with the Association for Research in Vision and Ophthalmology Resolution on the Use of Animals in Research. Prior to exposure the rabbits are anesthetized with an intramuscular injection of xylazine and ketamine hydrochloride (Rompun-Ketaset) in the proportions: 60% of 20 mg/ml Rompun to 40% of 100 mg/ml Ketaset by volume. In addition, a topical anesthesia (proparacaine

hydrochloride 1/2%) is applied to each eye before exposure and a drop of homatropine bromide 5% is instilled to dilate the pupil. This facilitates examination of the exposed corneas for minimal lesions. The anesthetized animals are placed in a conventional holder for exposure. A speculum is inserted in the eye about one minute before exposure and the eye irrigated with BSS solution (Alcon Surgical) which is at room temperature; however, in order to create a reproducible "tear film," the irrigation is stopped 20 sec before the exposure and excess fluid is blotted at the limbus. The cornea surface is assumed to have returned to its normal temperature after this time. One exposure is made to each eye. One-half hour after exposure the rabbits, still under anesthesia, are sacrificed with Beuthanasia-D administered in an ear vein. The eyes are enucleated and examined for damage using a Nikon FS-3 photo slit-lamp. In selected cases the globes are placed in gluteraldehyde/formaldehyde fixative and are delivered to Prof. W. R. Green's laboratory at the Wilmer Ophthalmological Institute where they are processed for microscopy and the micrographs evaluated by Dr. Green.

In a few experiments we exposed enucleated eyes which were at room temperature to test the damage mechanism. We have shown previously that reliable damage thresholds can be determined in freshly enucleated eyes.[8] For these experiments the rabbits were anesthetized and given a topical anesthesia and the pupils dilated exactly as was done for the *in vivo* exposures. The rabbits were then sacrificed and their eyes enucleated. The enucleated eyes were placed in room temperature (usually ~20 °C) BSS and allowed to equilibrate for at least 5 min. They were then exposed using the same protocol as for the *in vivo* exposures. After exposure the eyes were placed back in the BSS solution for 1/2 hr before examining them for damage.

The criterion that we use for minimal epithelial damage is that due to Brownell and Stuck[9], namely the presence of a superficial gray-white spot that develops within 1/2 hr after exposure. We have found that the damage threshold is sharply defined; i.e., only rarely is there overlap between exposures that produce minimal lesions and those that do not. Therefore we do not use statistical procedures such as probit analysis in order to determine the threshold, as these would require the use of more animals than we deem necessary. We make one exposure per eye, bracketing exposures above and below threshold. The bracket is narrowed until there is only about a 10% difference in energy between an exposure that produces a minimal lesion and one that does not. The threshold exposure is taken to be at the center of the bracket.

Temperature calculations are based on a Green's function solution to the heat conduction equation for an incident beam with a Gaussian irradiance profile that is absorbed according to Beer's law. The beam is assumed to impinge on a semi-infinite slab and to have a constant peak irradiance for the duration of the exposure. We also assume that conduction is the only mode of heat transfer and that no heat is lost to the air at the epithelial interface. The absorption coefficient and thermal properties are assumed to be those of water.[1, 2] The solution $T(r,z,t)$, where r is the radial distance from the beam axis, z is the depth into the cornea, and t is time, has the form of a definite integral that can be evaluated numerically.[1, 4, 10] Since our last Annual report we have made additional modifications to this program to facilitate the calculations for multiple-pulse exposures using very short pulses. The modifications are discussed below and a copy of the new program is listed in Appendix 2.

Results and Discussion

We noted in the first Annual Report covering the period 1 Nov. 1995-31 October 1996 that the experimental apparatus, which had not been in use since our previous contact expired in 1989 and which had been disassembled, was operational and that its operation had been verified on a few test exposures. As a result, most of the objectives in the original Statement of Work for the first year were shifted to this year. These objectives were:

1. The data base of threshold conditions for 80 ns pulses from CO_2-TEA lasers will be extended by measuring the threshold energy densities for sequences of 32, 128 and 1024 pulses at 10 Hz and sequences of 2, 8, 32 and 128 pulses at 20 Hz. The existing thresholds for 2 and 8 pulses at 10 Hz will be refined.

2. An understanding of the damage mechanism for such pulses will be pursued by:

   a) determining how lowering the temperature of the epithelium affects the threshold,

   b) obtaining light and electron micrographs of the damage,

   c) using high-speed photography to investigate ablation of material from the corneal surface, and

   d) measuring pressure transients in model systems.

3. The required characteristics of potential near-infrared laser source(s) for damage studies will be identified by performing detailed temperature calculations in the 1.3 to 2.5 μm wavelength region.

This year we have made significant progress toward achieving these objectives in spite of having had to move and re-establish our laboratory during the third quarter. The move to improved space was necessary because of a reorganization at the Applied Physics Laboratory.

We repeated and refined the determination of the damage threshold for 2 pulses at 10 Hz. The new threshold of 235 mJ/cm²/pulse is slightly higher than the value of 200 mJ/cm²/pulse that we had determined in preliminary experiments.[6, 7] We then confirmed our earlier value for the threshold for 8 pulses at 10 Hz. After these experiments we determined epithelial damage thresholds for sequences of 32, 128, and 1024 pulses at a pulse repetition frequency of 10 Hz. In order to perform the experiments with 32 or more pulses it was necessary to put a partially reflecting attenuator in the laser beam because the required pulse energies were below the lasing threshold. We found that the beam diameter measured with the partial reflector in place tended to be smaller than when it was removed. This led us to question the previously reported single-pulse threshold,[6, 7] because at the time it was determined our practice was to attenuate the beam so that the Spiracon detector used to measure beam diameter would not be saturated. We noted that if the unattenuated beam used in determining the threshold actually had a larger diameter, then the correct value of ED_{th} would be lower. Consequently we repeated the single-pulse threshold measurement without using the reflector. In these new experiments the beam intensity was reduced by decreasing the laser power. The newly determined threshold is 307 mJ/cm² compared to the value 360 mJ/cm² found previously. The final 10 Hz damage thresholds are listed in Table I together with the calculated peak temperature increases. The temperature calculations and their implications are discussed below. These threshold results were presented at the 1997 International Laser Safety

Conference[11] and at the annual meeting of the Association for Research in Vision and Ophthalmology.[12]

In the original Statement of Work we also were to determine epithelial damage thresholds at a pulse repetition frequency of 20 Hz. However, we discovered that output of the Boston Laser (Model 220S) was unstable at pulse frequencies above 16 Hz (although the specifications claimed 20 Hz). Boston Laser is no longer in business, consequently technical support for the laser is not available. We discussed this problem with our Contracting Officer's Representative, Mr. Bruce Stuck, and it was agreed that we would make the determinations at 16 Hz. The final results are listed in Table I (note that we made an additional threshold determination at 1024 pulses which was not included in the original Statement of Work).

Table 1: Threshold Energy Densities and Calculated Maximum Temperature Rises for Sequences of 80 ns Pulses.

Number of Pulses	Pulse Repetition Frequency (Hz)	Ed_{th} (mJ/cm²/pulse)	$d_{1/e}$ (mm)	ΔT_{max} (C)*
1	–	307	3.72	30.25
2	10	235	3.48	25.68
8	10	228	3.80	32.00
32	10	154	3.78	29.15
128	10	136	3.41	32.45
1024	10	95	3.21	26.60
2	16	265	3.62	29.73
8	16	205	3.75	31.26
32	16	150	3.73	32.90
128	16	105	3.82	32.80
1024	16	85	3.58	35.06

*Calculated on the beam axis 10 μm beneath the anterior tear surface.

The epithelial damage thresholds listed in Table 1 are plotted in Figure 1. The least squares fits to these data show that the thresholds at 10 Hz and 16 Hz are correlated by an empirical power law of the form

$$ED_{th} = CN^{-\alpha},$$

in which N is the number of pulses in the sequence. The coefficient C and exponent α appear to differ slightly for the two cases; however it is not possible to discern if the difference is real. For the 10 Hz threshold, C = 291 mJ/cm²/pulse and α = 0.162 (R = 0.976), and for the 16 Hz threshold, C = 300 mJ/cm²/pulse and α = 0.194 (R = 0.997). The least squares fits fall within the

±10 percent accuracy estimated from the bracketing procedure used in determining the thresholds. If both sets of data are assumed to be part of the same population we find C = 295.5 mJ/cm^2/pulse and α = 0.178 (R = 0.984). The power law is of the same form that we found previously for sequences of pulses having individual pulse durations between 0.001 and 1 sec and pulse repetition frequencies between 1 and 100 Hz, except that, for these longer pulses, the exponent α = 0.25 and the coefficient depended on the duration of the individual pulses.[5] Coincidentally, retinal damage thresholds for sequences of pulses are also described by a power law of this same form with α = 0.25.[13]

In order to calculate the temperature histories for these pulse sequences it was necessary to make minor modifications to our thermal program in order to obtain sufficient time resolution after the 80 ns pulses to capture the maximum temperature increase and yet not have too many points for a practical calculation. Thus the modification allowed for calculating temperatures at a number of

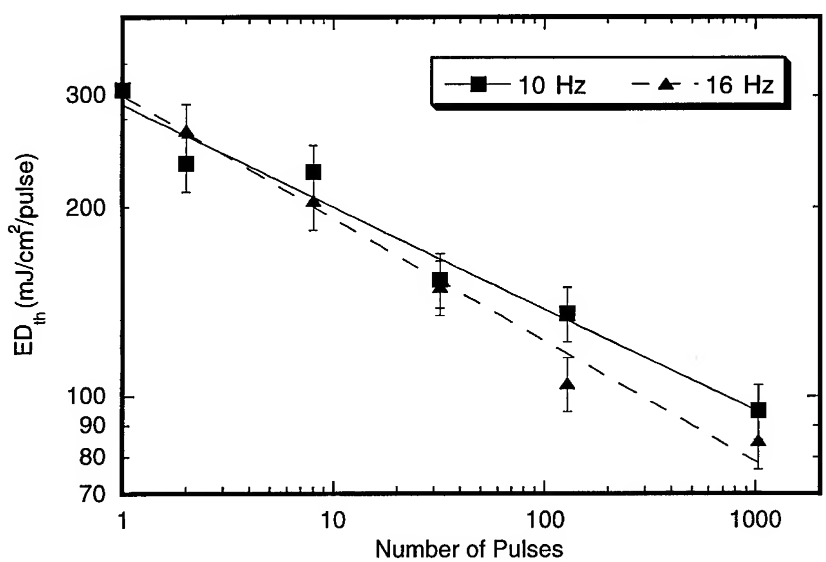

Figure 1. The dependence of the threshold energy density per pulse on the number of pulses at pulse frequencies of 10 and 16 Hz. The lines are least squares fits to a power law of the form $ED_{th} = CN^{-\alpha}$. The corresponding values of C and α are given in the text. The error bars are ±10 percent of the values and represent the estimated accuracy of the bracketing procedure used in determining the thresholds.

equally spaced points during each pulse and at a number of points with a wider interval between them after each pulse. The numbers of points during and after each pulse and the time interval after each pulse for which temperatures are calculated are inputs into the revised program. A listing of the revised program is given in Appendix 2.

We have completed the temperature calculations at the damage threshold for all of the 10 Hz and 16 Hz exposures. Figure 2 shows typical temperature histories at the damage threshold for

sequences of 32 and 128 pulses at a pulse repetition frequency of 16 Hz. The calculations are for the temperature history at a position on the beam axis, 10μm beneath the surface of the tear layer;

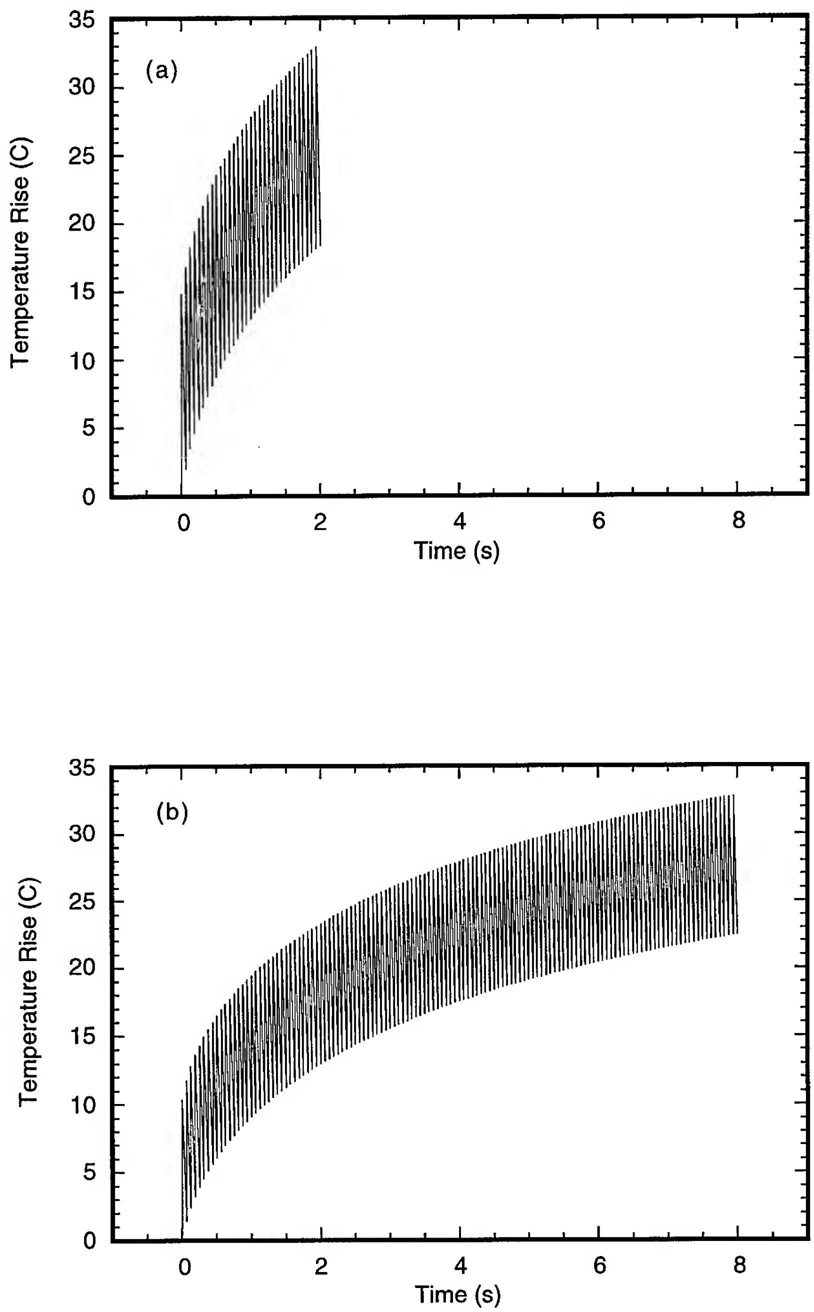

Figure 2. Calculated temperature histories on the beam axis 10 μm beneath the tear surface at the threshold exposure for sequences of 32 pulses, and (b) 128 pulses at 16 Hz.

thus, assuming a tear layer thickness of about 7 μm, the temperature history is that just inside the anterior-most epithelial cells.[5-7] Using the modified program we showed that the maximum temperature increase occurred ~164 μsec after the final pulse. The maximum temperature increases for all of the damage thresholds are listed in Table 1.

The damage condition is described by an essentially constant maximum temperature rise and is consistent with a critical peak temperature damage model. For the exposures at 10 Hz, damage occurs at ΔT_{max} = 29.4±2.8 C (mean±SD), and for the exposures at 16 Hz, it occurs at ΔT_{max} = 32.0±2.0 C. The maximum temperature rises for the two exposure conditions are shown graphically in Figure 3.

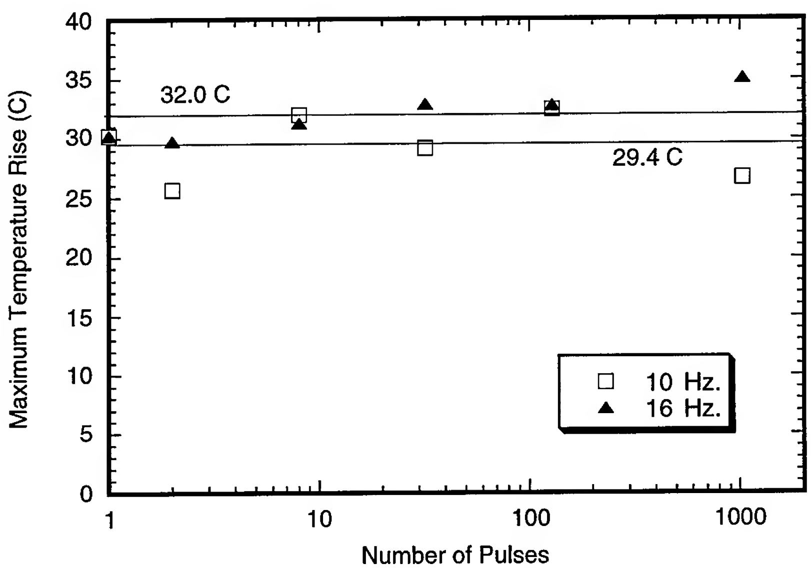

Figure 3. The calculated maximum temperature rises on the beam axis 10 μm beneath the tear surface for the damage threshold exposure. The lines show the mean values of ΔT_{max} for the two exposure conditions.

In the Introduction we noted that light and electron micrographs of corneas exposed to a single 80 ns pulse just above the damage threshold show features consistent with both thermal and mechanical (e.g., acoustic) damage.[6, 7] However, the fact that the calculated maximum temperature rises listed in Table 1 and plotted in Figure 3 are essentially constant for all of damage thresholds suggests that, at least for the multiple-pulse exposures, the damage mechanism may be predominately thermal.

In order to test this suggestion, we performed a series of damage experiments on enucleated eyes cooled to room temperature (average 21 C) as described in Methods. The underlying hypothesis for this test is that if the critical temperature model is valid, then damage should occur for exposures that result in the same final critical temperature (not temperature increase). Thus in a cornea initially at room temperature, sufficient additional energy would have to be supplied first to raise the temperature to the *in vivo* temperature and then to the final damage temperature. In a preliminary experiment using 8 pulses at 16 Hz we showed that corneas in the

cooled enucleated eyes did not incur damage at the same (slightly above threshold) exposure that produced a lesion in the *in vivo* cornea. This finding suggested that the damage mechanism was at least partially thermal. We then proceeded to determine damage thresholds in cooled corneas for sequences of 8 and 32 pulses at 16 Hz. The threshold energy densities and the calculated maximum temperature rises for these experiments are listed in Table 2. Assuming that the temperature of the anterior surface of an *in vivo* cornea is 35 C, the "damage temperatures" from Table 1 for the 8 and 32 pulse 16 Hz thresholds are respectively 339.5 K and 341.1 K; whereas they are respectively 354 K and 345.8 K in the corneas cooled to 21 C before exposure. The additional energy required to produce a minimal lesion in the cooled corneas is therefore sufficient to raise the cornea temperature to a level slightly higher than that associated with damage *in vivo*. These results are highly suggestive that the multiple pulse damage is indeed predominately thermal. We speculate that the increased "damage temperatures" in the enucleated eye experiments may be due a slowing down of the processes leading to the observed damage endpoint as a result of the lower ambient temperature. (Recall that we determine damage 1/2 hour after exposure and the enucleated eye is maintained in BSS at 21 C during this time.)

Table 2: Threshold Energy Densities and Calculated Maximum Temperature Rises for Enucleated Eyes at 21 C.

Number of Pulses	Pulse Repetition Frequency (Hz)	Ed_{th} (mJ/cm^2/pulse)	$d_{1/e}$ (mm)	ΔT_{max} (C)*
8	16	393	3.58	59.8
32	16	236	3.58	51.6

*Calculated on the beam axis 10 μm beneath the anterior tear surface.

We have submitted corneas with lesions to Dr. W. R. Green at the Wilmer Institute for histology. Corneas exposed slightly above the damage threshold for 8 pulses and 1024 pulses at 16 Hz were submitted prior to the end of this reporting period; however no results were available. We plan to submit additional tissue exposed just above the damage threshold for 8 pulses, 128 pulses, and 1024 pulses at 10 Hz and 128 pulses at 16 Hz.

Conclusions

Threshold damage to the corneal epithelium resulting from exposure to sequences of 80 ns pulses of CO_2 laser radiation is correlated by a power law of the form $ED_{th} = CN^{-\alpha}$ in which ED_{th} is the threshold energy density and N is the number of pulses in the sequence. The constant C and exponent α appear to differ slightly depending on the pulse repetition frequency. For sequences of pulses at 10 Hz, C = 291 mJ/cm^2/pulse and $\alpha = 0.162$ and for sequences at 16 Hz, C = 300 mJ/cm^2/pulse and $\alpha = 0.194$. Temperature calculations reveal that the maximum temperature increase on the beam axis 10 μm beneath the anterior tear surface resulting from the different threshold exposures is essentially constant. For the exposures at 10 Hz, damage occurs at ΔT_{max} = 29.4±2.8 C (mean±SD), and for the exposures at 16 Hz, it occurs at ΔT_{max} = 32.0±2.0 C. This result is consistent with a critical peak temperature damage model and suggests that, at least for the multiple-pulse exposures, the damage mechanism may be predominately thermal. Damage threshold measurements on corneas maintained at 21 C indicated that the damage mechanism is indeed predominately thermal.

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Appendix 1

Personnel Paid by Contract DAMD17-96-C-6005:

R. L. McCally, Ph. D.	Principal Investigator
C. B. Bargeron, Ph. D.	co - Principal Investigator
C. D. Carter	Group Secretary

APPENDIX 2

Modified program for calculating temperature histories for sequences of very short pulses. Program allows for variable resolution following pulses.

```
C      PROGRAM CALCULATES TEMPERATURE-TIME HISTORIES FOR RADIATION
   INCIDENT
C   ON A SEMI-INFINITE ABSORBING SLAB
C   RADIATION CAN BE EITHER CW OR SEQUENCES OF PULSES
C   RADIATION AND CONVECTIVE HEAT TRANSFER ARE IGNORED
C    PROGRAM ADAPTED BY R. MCCALLY SEPTEMBER 25, 1997 FROM PROGRAM
   TCAL.F TO PROVIDE INCREASED TIME
C   RESOLUTION AFTER PULSES
C
C   S0    = IRRADIANCE (W/(CM*CM))
C   KAPPA = THERMAL CONDUCTIVITY (CAL/(CM*DEGC))
C   R     = RADIAL DIST FROM BEAM AXIS (CM)
C   Z     = DEPTH (CM)
C   RE    = 1/E BEAM RADIUS (CM)
C   TAU   = PULSE DURATION (SEC)
C   TAAFT = INCREASED RESOLUTION INTERVAL AFTER PULSES
C   C     = HEAT CAPACITY (CAL/(GM*DEGC))
C   GAM   = INVERSE ABSORBTION LENGTH (1/CM)
C   DELT  = 1/PRF (SEC)  --- DELT MUST BE >= TAU
C   NP    = NUMBER OF PULSES
C   ND    = NUMBER OF INTERVALS CALCULATED DURING EACH PULSE
C   NDAP  = NUMBER OF POINTS IN THE INTERVAL TAAFT AFTER EACH PULSE
C    NPTS   = NUMBER OF CALCULATED POINTS = NP*(ND+NDAP) + 1   (CALC IN
   PGM)
C   NRUNS = NUMBER OF SETS OF INPUT DATA
C
C   IRULE  - CHOICE OF QUADRATURE RULE IN DQDAG.  (INPUT)
C         A GAUSS-KRONROD RULE IS USED WITH
C             7 - 15 POINTS IF IRULE = 1
C            10 - 21 POINTS IF IRULE = 2
C            15 - 31 POINTS IF IRULE = 3
C            20 - 41 POINTS IF IRULE = 4
C            25 - 51 POINTS IF IRULE = 5
C            30 - 61 POINTS IF IRULE = 6
C         IRULE = 2 IS RECOMMENDED FOR MOST FUNCTIONS.
C         IF THE FUNCTION HAS A PEAK SINGULARITY USE IRULE = 1.
C         IF THE FUNCTION IS OSCILLATORY USE IRULE = 6.
C
   PROGRAM IRTEMP
C
   IMPLICIT REAL*8(A-H,O-Z)
   REAL*8 KAPPA
   COMMON/BLOCKA/      ZO,ONE,TWO,TEN,HUN,SPI,W,ZA,GTA,AZ,E2,R2,      XO,
   TEGZ, G2FA
```

```
      DIMENSION TIME(0:62000), T1(0:62000), TEMP(0:62000),TEMPN(0:62000)
C     T1 ARE TIME POINTS DURING AND AFTER A SINGLE PULSE
      CHARACTER*1 TAB
      EXTERNAL FF
C
      INN = 7          ! DEFINES INPUT LOGICAL UNIT
      IOUT = 8         ! DEFINES OUTPUT LOGICAL UNIT FOR FINAL DATA FILE
      ISCREEN = 6      ! DEFINES LOGICAL UNIT FOR OUTPUT TO SCREEN
      ICOUNT = 0       !INITIALIZE COUNTER FOR TIMES INPUT FILE IS ACCESSED
C
C     DEFINE CONSTANTS
      ZO = 0.0D0
      ONE = 1.0D0
      TWO = 2.0D0
      TEN = 10.0D0
      HUN = 100.0D0
      PI = 4.0D0 * DATAN( ONE )
      SPI = DSQRT( PI )
      TAB = CHAR(9)     ! TAB IS ASC 9
C
C     OPEN I/O FILES
      OPEN (UNIT=INN, FILE ='IRINHRES', STATUS='OLD',ACCESS='SEQUENTIAL',
      BLANK='NULL')
      OPEN (UNIT=IOUT, FILE ='IROUT.HIRES',
      STATUS='UNKNOWN',ACCESS='SEQUENTIAL')
C
 1000 CONTINUE
C
C     GET INPUT DATA
      CALL
      INPUT(S0,KAPPA,R,Z,RE,TAU,TAAFT,C,GAM,DELT,NP,ND,NDAP,RHO,NRUNS,I
      COUNT,
       1INN,IOUT,ISCREEN,AERR,RERR,IRULE)
C
      NT = ND+NDAP
       NPTS = NP*(NT+1)
       WRITE(ISCREEN,3)NPTS
      WRITE(IOUT,3)NPTS
C
      A2 = RHO*C/(4.0D0*KAPPA)
      TSIG = RE*RE
      R2 = R*R
      FRONT = S0*GAM/(8.36D0*RHO*C)
      ZA = Z**2 * A2
      AZ = DSQRT( ZA )
      TA = TWO * DSQRT( A2 )
      GTA = GAM/TA
      XO = TWO*A2*Z/GAM
      TEGZ = TWO * DEXP(-GAM*Z)
      G2FA = GAM**2 / (4.D0*A2)
      W = A2 * TSIG
C
C     CALCULATE TIME POINTS
      DO 30 I=0,ND
```

```
        T1(I) = I*TAU/ND
   30 CONTINUE
C
      ND1 = ND + 1
C
      DO 31 I=ND1,NT
        T1(I) = TAU + (I-ND)*TAAFT/NDAP
   31 CONTINUE
C
      IF (NP.EQ.1) GO TO 38
C
      DO 36 J=1,NP
        JNT = (J-1)*(NT+1)
                DO 32 I=JNT,JNT+ND
                        K = I - JNT
                        TIME(I) = T1(K) + (J-1)*DELT
   32           CONTINUE
                DO 33 I=JNT+ND1,JNT+NT
                        K = I - JNT
                        TIME(I) = T1(K) + (J-1)*DELT
   33           CONTINUE
   36 CONTINUE
C
      GO TO 40
C
   38 DO 39 I=0,NT
        TIME(I) = T1(I)
   39 CONTINUE
C
   40 TIME(NPTS) = NP*DELT
C
C     BEGIN TEMPERATURE CALCULATION
      TEMP(0) = ZO
C      WRITE(ISCREEN,4)
C      WRITE(IOUT,5)TAB,TAB,TAB,TAB
C
      DO 100 I=1,NPTS
        TL = TIME(0)
        IF(TIME(I)-TAU .GT. TL) TL=TIME(I)-TAU
        TU = TIME(I)
        CALL DQDAG (FF, TL, TU, AERR, RERR, IRULE, PSI, ERREST)
C      DQDAG IS AN IMSL ROUTINE FOR EVALUATING THE INTEGRAL.  IT IS A
C        GLOBALLY ADAPTIVE SCHEME THAT IS BASED ON GAUSS-KONRAD
C        RULES
        TEMP(I) = FRONT * PSI
C       WRITE(ISCREEN,6) I,PSI,TIME(I),TEMP(I),ERREST
C       WRITE(IOUT,7) I,TAB,PSI,TAB,TIME(I),TAB,TEMP(I),TAB,ERREST
  100 CONTINUE
C
      DO 150 I=0,NPTS
        TEMPN(I) = TEMP(I)
  150 CONTINUE
      IF (NP.EQ.1) GO TO 375
```

```
C
C   HANDLE MULTIPLE PULSES
C
    DO 300 J=2,NP
        JNT = (J-1)*(NT+1)
                DO 200 I=0,NPTS
                        IF (I.LT.JNT) THEN
                                TEMPN(I) = TEMPN(I)
                        ELSE
                                TEMPN(I) = TEMPN(I) + TEMP(I-JNT)
                        END IF
 200            CONTINUE
 300 CONTINUE
C
C   WRITE TO FINAL DATA FILE
 375 WRITE(IOUT,380)TAB,TAB         ! WRITE HEADER FOR RESULTS
    DO 400 I=0,NPTS
        WRITE(IOUT,390) I,TAB,TIME(I),TAB,TEMPN(I)
 400 CONTINUE
    IF (ICOUNT .LT. NRUNS) GO TO 1000
  99 STOP
   3 FORMAT(' NPTS    = ',I5,'          TOTAL POINTS ')
   4 FORMAT(T3,'I',T11,'PSI',T25,'TIME',T36,'TEMPERATURE',T52,'ERROR')
   5 FORMAT('I',A1,'PSI',A1,'TIME',A1,'TEMPERATURE',A1,'ERROR')
   6 FORMAT(I5,1PG14.6,1PG14.6,1PG14.6,1PG14.6)
   7 FORMAT(I5,A1,1PG14.7,A1,1PG14.7,A1,1PG14.7,A1,1PG14.7)
 380 FORMAT('I',A1,'TIME',A1,'TEMPERATURE')
 390 FORMAT(I5,A1,1PE14.8,A1,1PE14.8)
    END
C
C
    FUNCTION  FF ( X )
C   THIS DESCRIBES THE INTEGRAND
    IMPLICIT REAL*8(A-Z)
    COMMON/BLOCKA/   ZO,ONE,TWO,TEN,HUN,SPI,W,ZA,GTA,AZ,E2,R2,XO,
   1TEGZ, G2FA
C
    IF(X .EQ. ZO) GO TO 50
C
    X2 = DSQRT( X )
    XW = ONE + X/W
    EE = -R2/XW
    E1 = ZO
    IF(DABS(EE) .LE. HUN) E1 = DEXP( EE )
C
    E2 = -ZA/X
C
    C1 = GTA * X2
    C2 = AZ/X2
    ARG1 = C1 + C2
    ARG2 = C1 - C2
    H1 = HFUN( ARG1 )
    H2 = HFUN( ARG2 )
C
```

```
      IF(X .GT. XO) GO TO 10
C...    FOR X LESS THEN XO AND NOT ZERO     6/2/80   THE REVISION
      FO = E1/XW
      G1 = TEGZ * DEXP(G2FA*X)
      G2=ZO
      IF(DABS(E2) .GT. HUN) GO TO 30
        H1 = HFUN( DABS(ARG1) )
        H2 = HFUN( DABS(ARG2) )
      G2 = (H1-H2)
C
   30 FF = FO*(G1 + G2)
      RETURN
C
   10 CONTINUE
      FF = E1 * (H1 + H2) / XW
      RETURN
C...     FOR X= 0 ONLY
   50 CONTINUE
      FF = TEGZ * DEXP(-R2)
      RETURN
      END
C
C
      FUNCTION HFUN ( ARG )
      IMPLICIT REAL*8(A-Z)
      COMMON/BLOCKA/   ZO,ONE,TWO,TEN,HUN,SPI,W,ZA,GTA,AZ,E2,R2,  XO,
     1TEGZ, G2FA
      DATA HALF,ONEH / 0.5D0, 1.50D0/
C
      Y = DABS( ARG )
      Y2 = Y*Y
      HFUN = ZO
      BB = Y2 + E2
      IF(ARG .GE. -13.0D0) GO TO 10
        B1=ZO
        IF(DABS(BB) .LE. 174.0D0) B1 = TWO * DEXP( BB )
        B2 = ZO
        IF(DABS(E2) .LT. 174.0D0)  B2 = DEXP(E2) /
     *  (SPI*(Y+HALF/(Y+ONE/(Y+ONEH/(Y+TWO/Y)))) )
        HFUN = B1 - B2
        RETURN
   10 CONTINUE
      IF(ARG .GE. ZO) GO TO 20
      IF(DABS(BB) .LT. 174.0D0) HFUN = DEXP(BB)*(TWO-DERFC(Y))
      RETURN
   20 CONTINUE
      IF(ARG .GT. 13.0) GO TO 30
      IF(DABS(BB) .LT. 174.0D0) HFUN = DEXP(BB)*DERFC(ARG)
      RETURN
   30 CONTINUE
      IF(DABS(E2) .GT. 174.0D0) GO TO 40
      Z = ARG
      HFUN = SPI*(Z+HALF/(Z+ONE/(Z+ONEH/(Z+TWO/Z))))
      IF(HFUN .NE. ZO) HFUN = DEXP(E2)/HFUN
```

```
 40 RETURN
    END
C
C
      FUNCTION DERFC(X)
C
C  RETURNS THE COMPLIMENTARY ERROR FUNCTION
C
C  CHECKS WITH MATHEMATICA TO 15 SIGNIFICANT FIGURES
C    IN RANGE (.001 <= X <= 4.0) (MAXIMUM PRINTOUT FROM MATHEMATICA
C     AND MAXIMUM RANGE CHECKED  3/18/96 RLM)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
      IF(X.LT.Z0)THEN
        DERFC=ONE+GAMMP(HALF,X**2)
      ELSE
       DERFC=GAMMQ(HALF,X**2)
      ENDIF
      RETURN
      END
C
      FUNCTION GAMMP(A,X)
      IMPLICIT REAL*8 (A-H,O-Z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
      IF(X.LT.Z0.OR.A.LE.Z0)PAUSE
      IF(X.LT.A+ONE)THEN
       CALL GSER(GAMSER,A,X,GLN)
       GAMMP=GAMSER
      ELSE
       CALL GCF(GAMMCF,A,X,GLN)
       GAMMP=ONE-GAMMCF
      END IF
      RETURN
      END
C
      FUNCTION GAMMQ(A,X)
      IMPLICIT REAL*8 (A-H,O-Z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
      IF(X.LT.Z0.OR.A.LE.Z0)PAUSE
      IF(X.LT.A+ONE)THEN
       CALL GSER(GAMSER,A,X,GLN)
       GAMMQ=ONE-GAMSER
      ELSE
       CALL GCF(GAMMCF,A,X,GLN)
      GAMMQ=GAMMCF
      ENDIF
      RETURN
      END

C
      SUBROUTINE GSER(GAMSER,A,X,GLN)
      IMPLICIT REAL*8 (A-H,O-Z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
```

```
      PARAMETER (ITMAX=400,EPS=10D-17)
      GLN = 0.5723649429247001D0            ! LN(SQRT(PI)) = GAMMA(1/2)
      IF(X.LE.Z0)THEN
        IF(X.LT.Z0)PAUSE
        GAMSER=Z0
        RETURN
      END IF
      AP=A
      SUM=ONE/A
      DEL=SUM
      DO 11 N=1,ITMAX
        AP=AP+ONE
        DEL=DEL*X/AP
        SUM=SUM+DEL
        IF(DABS(DEL).LT.DABS(SUM)*EPS)GO TO 1
11    CONTINUE
      PAUSE 'A TOO LARGE, ITMAX TOO SMALL
1     GAMSER=SUM*DEXP(-X+A*DLOG(X)-GLN)
      RETURN
      END
C
      SUBROUTINE GCF(GAMMCF,A,X,GLN)
      IMPLICIT REAL*8 (A-H,O-Z)
      DATA Z0,HALF,ONE/0.0D0,0.5D0,1.0D0/
      PARAMETER (ITMAX=400,EPS=10D-17)
      GLN = 0.5723649429247001D0            ! LN(SQRT(PI)) = GAMMA(1/2)
      GOLD=Z0
      A0=ONE
      A1=X
      B0=Z0
      B1=ONE
      FAC=ONE
      DO 11 N=1,ITMAX
        AN=DFLOAT(N)
        ANA=AN-A
        A0=(A1+A0*ANA)*FAC
        B0=(B1+B0*ANA)*FAC
        ANF=AN*FAC
        A1=X*A0+ANF*A1
        B1=X*B0+ANF*B1
        IF(A1.NE.Z0)THEN
          FAC=ONE/A1
          G=B1*FAC
          IF(DABS((G-GOLD)/G).LT.EPS)GO TO 1
          GOLD=G
        ENDIF
11    CONTINUE
      PAUSE 'A TOO LARGE, ITMAX TOO SMALL'
1     GAMMCF=DEXP(-X+A*DLOG(X)-GLN)*G
      RETURN
      END
C
C----------------------------------------------------------------------
      SUBROUTINE INPUT(S0,KAPPA,R,Z,RE,TAU,TAAFT,C,GAM,DELT,NP,ND,
```

```
     1NDAP,RHO,NRUNS,ICOUNT,INN,IOUT,ISCREEN,AERR,RERR,IRULE)
C------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 KAPPA
C     INTEGER*4 NPTS,NP,ND,NDAP,NRUNS,ICOUNT,INN,IOUT,ISCREEN,IRULE,I
      CHARACTER*9 DAY
      CHARACTER*11 AD1
      CHARACTER*30 AIN2
C
C PURPOSE:  READ INPUT FILE IRINPUT AND WRITE PARAMETERS.
C
C INPUT:    INN,IOUT,ISCREEN
C
C
C OUTPUT:   S0,KAPPA,R,Z,RE,TAU,TAAFT,C,GAM,DELT,NP,ND,NDAP,
C           RHO,NRUNS,ICOUNT,AERR,RERR,IRULE.
C
      ICOUNT=ICOUNT+1                ! INCREMENT FILE ACCESS COUNTER
C     READ FILE INN.
C
      READ(INN,'(A30)',END=99,IOSTAT=I)AIN2          ! READ HEADER
      READ(INN,'(A30)',END=99,IOSTAT=I)AIN2          ! READ ---
      READ(INN,'(A11)',END=99,IOSTAT=I)AD1           ! READ123 ETC
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,NRUNS
      READ(INN,'(A11,1PG14.6)',END=99,IOSTAT=I)AD1,S0
      READ(INN,'(A11,1PG14.6)',END=99,IOSTAT=I)AD1,TAU
      READ(INN,'(A11,1PG14.6)',END=99,IOSTAT=I)AD1,TAAFT
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,RE
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,Z
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,R
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,NP
      READ(INN,'(A11,1PG14.6)',END=99,IOSTAT=I)AD1,DELT
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,ND
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,NDAP
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,GAM
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,C
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,KAPPA
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,RHO
C.....INTEGRATION PARAMETERS:
      READ(INN,'(A11,F14.9)',END=99,IOSTAT=I)AD1,AERR
      READ(INN,'(A11,1PD14.9)',END=99,IOSTAT=I)AD1,RERR
      READ(INN,'(A11,I5)',END=99,IOSTAT=I)AD1,IRULE
C
C WRITE INPUT TO FILE IROUT ( DISK DATA FILE)
C
      WRITE(IOUT,100)
      WRITE(IOUT,105)
      CALL DATE(DAY)
      WRITE(IOUT,110)DAY
      AIN2 = ' INPUT PARAMETERS'
      WRITE(IOUT,110)AIN2
      WRITE(IOUT,150)NRUNS
      WRITE(IOUT,151)S0
      WRITE(IOUT,152)TAU
```

```
      WRITE(IOUT,167)TAAFT
      WRITE(IOUT,153)RE
      WRITE(IOUT,154)Z
      WRITE(IOUT,166)R
      WRITE(IOUT,155)NP
      WRITE(IOUT,156)DELT
      WRITE(IOUT,157)ND
      WRITE(IOUT,158)NDAP
      WRITE(IOUT,159)GAM
      WRITE(IOUT,160)C
      WRITE(IOUT,161)KAPPA
      WRITE(IOUT,162)RHO
      AIN2 = ' INTEGRATION PARAMETERS:  '
      WRITE(IOUT,110)AIN2
      WRITE(IOUT,163)IRULE
      WRITE(IOUT,164)AERR
      WRITE(IOUT,165)RERR
C
C WRITE INPUT TO SCREEN
C
      WRITE(ISCREEN,100)
      WRITE(ISCREEN,110)DAY
      AIN2 = ' INPUT PARAMETERS'
      WRITE(ISCREEN,110)AIN2
      WRITE(ISCREEN,150)NRUNS
      WRITE(ISCREEN,151)S0
      WRITE(ISCREEN,152)TAU
      WRITE(ISCREEN,167)TAAFT
      WRITE(ISCREEN,153)RE
      WRITE(ISCREEN,154)Z
      WRITE(ISCREEN,166)R
      WRITE(ISCREEN,155)NP
      WRITE(ISCREEN,156)DELT
      WRITE(ISCREEN,157)ND
      WRITE(ISCREEN,158)NDAP
      WRITE(ISCREEN,159)GAM
      WRITE(ISCREEN,160)C
      WRITE(ISCREEN,161)KAPPA
      WRITE(ISCREEN,162)RHO
      AIN2 = ' INTEGRATION PARAMETER:  '
      WRITE(ISCREEN,110)AIN2
      WRITE(ISCREEN,163)IRULE
      WRITE(ISCREEN,164)AERR
      WRITE(ISCREEN,165)RERR
99    CONTINUE
C
C FINAL WRITE STATEMENTS
C
      WRITE(IOUT,120)
      WRITE(ISCREEN,120)
      RETURN
C
100   FORMAT(/' ---WE ARE IN IRINHRES --- '/)
105   FORMAT(/' --- FILE IROUT.HIRES--- '/)
```

```
110  FORMAT(A35)
120  FORMAT(/' ---LEAVING IRINHRES--- '/)
130  FORMAT(' ... ')
150  FORMAT(' NRUNS   = ',I5)
151  FORMAT(' SO      = ',1PG14.5,' WATTS/CM**2')
152  FORMAT(' TAU     = ',1PG14.5,' SEC')
153  FORMAT(' RE      = ',F14.5,' CM')
154  FORMAT(' Z       = ',F14.5,' CM')
155  FORMAT(' NP      = ',I5,'          PULSES')
156  FORMAT(' DELT    = ',1PG14.5,' SEC')
157  FORMAT(' ND      = ',I5,'          POINTS/PULSE')
158  FORMAT(' NDAP    = ',I5,'          POINTS AFTER PULSE')
159  FORMAT(' GAM     = ',F14.5,' 1/CM')
160  FORMAT(' C       = ',F14.5,' CAL/(GM*DEGC)')
161  FORMAT(' KAPPA   = ',F14.5,' CAL/(CM**2*DEGC)')
162  FORMAT(' RHO     = ',F14.5,' GM/CM**2')
163  FORMAT(' IRULE   = ',I5)
164  FORMAT(' AERR    = ',F14.5)
165  FORMAT(' RERR    = ',1PD14.5)
166  FORMAT(' R       = ',F14.5,' CM')
167  FORMAT(' TAAFT   = ',1PG14.5,' SEC')
     END
```